A REVIEW OF CONTROL METHODS OF MULTILEVEL INVERTERS

An IAESTE Internship Project Report submitted by

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BONAFIDE CERTIFICATE

This is to certify that this report entitled, "**A REVIEW OF CONTROL METHODS OF MULTILEVEL INVERTERS**", is a bonafide work of the following candidate from University of Jordan, who carried out the IAESTE Internship project work under my supervision during the academic year 2019-20. / **Summer 2019**.

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ABSTRACT

In a continuous quest to improve efficiency of power conversion, multiple methods have been applied to control the performance of multilevel inverters, this study focuses on comparing a uniform step firing angles, multicarrier pulse width modulation (MCPWM) and harmonic elimination strategy (HES) using artificial neural networks for a five-level inverter. It has been shown that for a multilevel inverter to work efficiently more levels should be added; the more the levels the less the harmonic distortion. Therefore, it was the 2^{nd} order RC filter that made the biggest impact on the harmonic distortion of the signal. Several tests were applied and recorded on the MCPWM and the HES techniques with varying modulation rates and modulation indices, with and without a filter to be able to judge from several angles and for different applications.

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Chapter 1

INTRODUCTION

Humans are characterized by constant adapting to the surrounding environment and the changes that occur around them, we discovered electricity and made breakthroughs and innovations to make electricity accessible and suitable to wide range of applications, specifically DC and AC breakthroughs. This report will be focusing on inverters.

Inverters are power electronic devices that convert DC to AC, it's usually used to convert electricity from a storage unit, e.g. Battery, to feed an AC actuator or to make use of renewable energy sources such as solar panels and feed the main grid. Other applications include uninterruptible power supply "UPS" where energy is stored in the form of DC current, if the main grid current is disconnected the UPS converts DC to AC until the main grid connects again. Additionally, inverters are heavily used in drives and control systems, to control the power delivered to electric actuators and electric machines. [1]

OBJECTIVES

1. To be familiar about latest technologies and techniques regarding inverters.
2. To learn about various topologies of multilevel inverter.
3. To gain in-depth knowledge of H-Bridge cascaded multilevel inverter topology.
4. To observe the impact of various control methods on the efficiency of a five-level cascaded multilevel inverter.

Chapter 2

LITERATURE REVIEW

Overview of development stages of inverters:

In the late nineteenth century, and due to the growing need to control the properties of generated and transmitted electricity, engineers and scientists have achieved breakthroughs and innovations by mechanical means such as rotary converters and motor generator sets, where commutators are connected to rotating coils within a stationary field coils, these commutators rectify the current. [2]

In 1904, the diode was invented by the English engineer and physicist Sir John Ambrose Fleming, the diode was simply a vacuum tube with a heated electron emitting cathode and an anode, preventing the current from flowing bidirectionally. [3]

The next breakthrough was achieved in the 1940s with the invention of semiconductor devices, enabling us to better control the flow of electrons. Thus, increasing efficiency and reliability which manifested in the 1960s by the invention of the transistors.

The standard and simplest type of inverters is composed of an H-bridge-shaped four transistors, synchronized to achieve bi-directional current to mimic the alternating current as shown in figure (2.1).

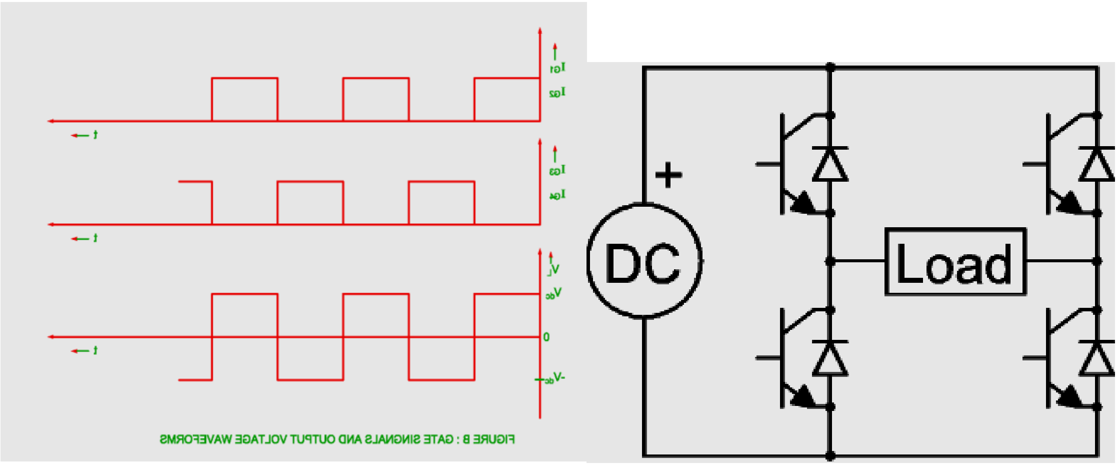

Figure 2.1.H-Bridge Inverter (right) and typical output (left) [4]

This type of inverters had many shortcomings such as losses in the form of harmonic distribution and a very high rate of change of voltage with respect to time (dV/dt), the quest for an improved performance had led to the adoption of multilevel inverters. [5]

Concept of multilevel inverters

Multilevel inverter is based on mimicking a typical sinusoidal wave, where the voltage/current is monotonically increasing and then decreasing. To achieve this, we applied gradual increase characterized by levels of voltage until we reach the desired amplitude, so instead of applying one large step we divided it into multiple steps accumulating as shown in figure (2.2).

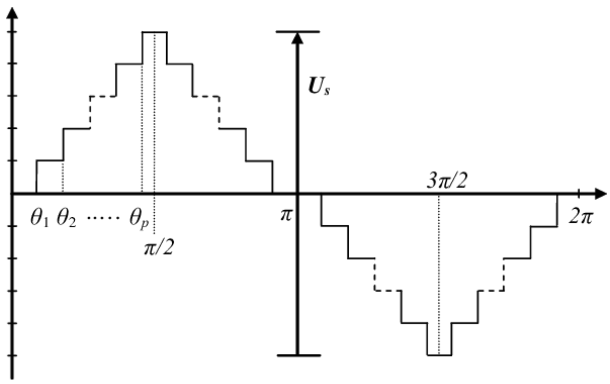

Figure 2. 2.Typical Output of Multilevel Inverter Voltage

Different topologies of multilevel inverter:

Several topologies can be applied to achieve the desired gradual increase in voltage, including Diode Clamped Inverter, Flying Capacitor Inverter, Cascaded H-Bridge Inverter and Hybrid Inverter, further comparisons and details regarding these topologies are discussed in [6].

In this study, H-Bridge Cascaded multilevel inverter was chosen due to its wide adoption and simple robust structure allowing for more flexibility in converting the powder.

H-Bridge Cascaded Multilevel inverter

The general scheme of a cascaded multilevel inverter is shown on figure (2.3), it’s composed of an H-Bridges powered by independent DC-sources, these bridges are connected in series as to accumulate the voltage within one cycle. The equation for the number of levels a cascaded MLI is given as:

$$L = 2 * n + 1 \quad \text{--} \ (2.1)$$

DC voltage sources can be either variant or unequal, which are then called asymmetric multilevel inverter, or we can use equal amplitude of DC-voltage feeding and the topology would be characterized as symmetric multilevel inverter, which is the focus of this study.

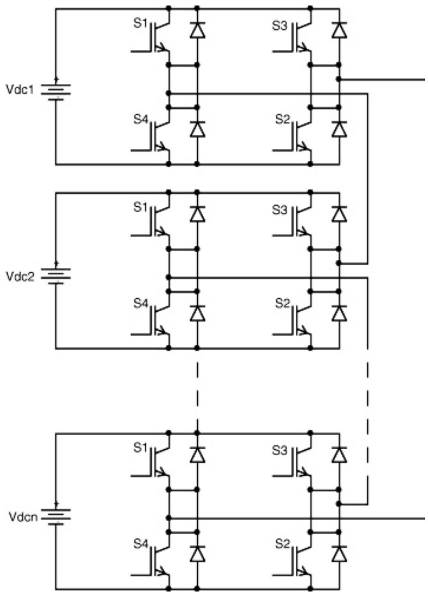

Figure 2.3. H-Bridge Cascaded Multilevel Inverter General Scheme [7]

The purpose behind the innovation of multilevel inverter was to build a highly efficient inverter with low harmonics. To achieve this goal, multiple modifications were applied to achieve the optimum control strategy resulting in the lowest total harmonic distribution while maintaining viability, robustness and affordability to apply on a large scale, some methods use high switching frequencies while others use low switching frequencies. The various methods are illustrated in figure (2.4).

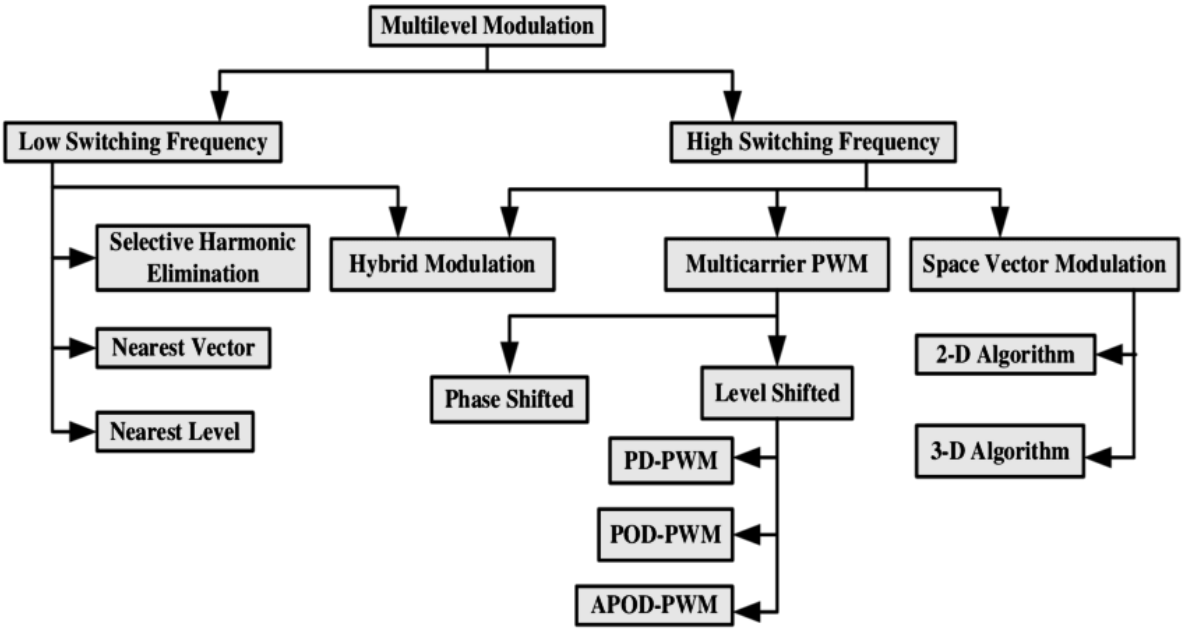

Figure 2.4. Multilevel Inverter Modulation Methods

In this study we have compared three methods for controlling the pulses fed to five-level cascaded SMLI:

1. Random Firing Angle PWM.

The main aim was to build five-level inverter voltage waveform as a basis for comparisons, the firing angles were chosen randomly within a quarter of a period.

2. Multicarrier Pulse Width Modulation MCPWM.

The concept behind MCPWM is that we're trying to mimic a sinusoidal signal; that is achieved by comparing a triangular pulse with the reference sinusoidal pulse, implicitly giving more weight to the generated pulse when the reference pulse at its peak and gradually reducing the width of the pulse as the reference signal decreasing. The reference signal has an amplitude A_r and a frequency of F_r, while each of the triangular signals has the same amplitude A_c and the same frequency F_c, while there are multiple methods of achieving MCPWM technique, this study focuses on level shifted phase disposition (PD) carrier signals. Further details about the types of MCPWM technique and their differences can be found in [8].

3. Harmonic Elimination Strategy Using Artificial Neural Network.

Harmonic Elimination strategy is yet another method of controlling a multilevel inverter using low switching frequency, it is based on the Fourier analysis of the generated voltage [9], the total output voltage waveform is composed of the fundamental sinusoidal voltage, in addition to infinite harmonics in the form of multiples of the fundamental frequency. The purpose is to represent the signal mathematically then eliminate preselected harmonics. The general form of Fourier series is given by:

$$f(x) = a_0 + \sum_1^\infty a_n \sin(nwt) + \sum_1^\infty b_n \cos(nwt) \text{ ----------------------(2.2)}$$

And the parameter values are given by:

$$a_0 = \frac{1}{2\pi}\int_0^{2\pi} f(X).dx \text{ -- (2.3)}$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\sin(nwt).dwt \text{ ----------------------------(2.4)}$$

$$b_n = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos(nwt).dwt \text{ -----------------------------(2.5)}$$

Analysing the five-level voltage waveform model in figure (2.2), it's noticed that the signal is symmetric along the x-axis, indicating that DC component $a_0 = 0$. Moreover, since the signal is odd, there are no even harmonics, $b_n = 0$ for all values of n. [10]

Since the signal is repetitive every quarter of a cycle, the parameter a_n for a five-level inverter can be written as:

$$a_n = \frac{4}{\pi}\left(\int_{\alpha 1}^{\pi/2} V_I \sin(nwt).dwt + \int_{\alpha 2}^{\pi/2} V_I \sin(nwt).dwt\right) \text{ --------------(2.6)}$$

After performing the integration, the value of a_n is given by:

$$a_n = \frac{4V_I}{\pi n}(\cos n\alpha_1 + \cos n\alpha_2) \text{ ---------------------------------- (2.7)}$$

According to equation (2.7), in order to eliminate the third harmonic and control the output value, the following system of equations has to be solved for the two unknowns α_1 and α_2:

$$\cos 3\alpha_1 + \cos 3\alpha_2 = 0 \quad \text{----------------------------------(2.8)}$$

$$\cos \alpha_1 + \cos \alpha_2 = r \times \frac{\pi}{4}$$

$$r = \frac{V_{desired}}{V_{input}} \times n \;; V_{desired} \leq V_{input} \quad \text{--------------------------------(2.9)}$$

There are multiple numerical and iterative methods to solve a system of non-linear equations. Namely, Taylor's Polynomial [11], quadrature formulas [12] and other techniques, these techniques can be evaluated by the accuracy of the solution, convergence speed, computational burden and robustness.

Since there are infinite possibilities of modulation indices, and instead of solving a set of equations every time the modulation index changes, neural networks were used to approximate and fit a function that solves the firing angles for all values of r.

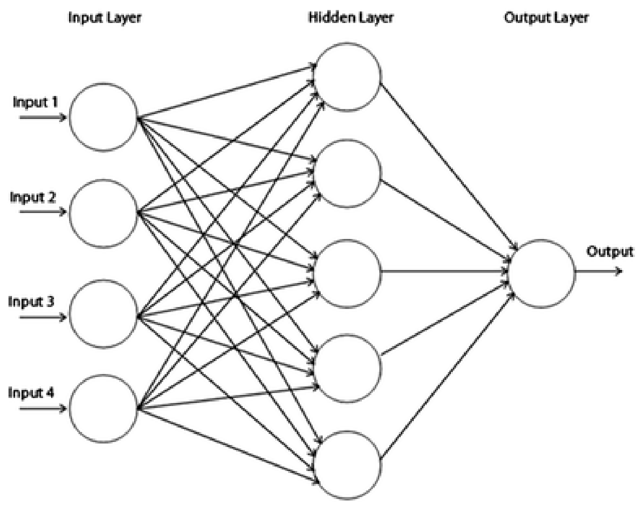

Figure 2.5.Structure of an artificial neural network

Artificial neural network (ANN) is named based upon the neurons of human brain. They're widely used in classification and optimization problems due to their ability to efficiently generalize functions and fit data. ANN is now a crucial component in communication, control and economics. A neuron performs the weighted sum of the input signal and the connecting weight. The sum is added with the bias or threshold and the resultant signal is then passed through a nonlinear function of sigmoid or hyperbolic tangent type. The thresholds and the weights are constantly updated and changed to match the desired output [13]. The structure of a neural network is shown in figure (2.5), there could a varying number of inputs, outputs and hidden layers depending on the purpose of the network.

The block diagram for supervised ANN is shown in figure (2.6).

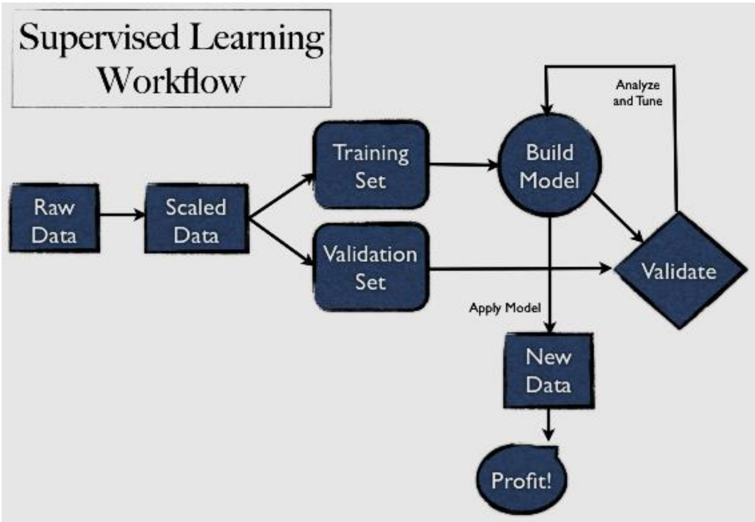

Figure 2.6. Supervised learning workflow [14]

Chapter 3

METHODOLOGY AND RESULTS

- **Random Firing Angles PWM:**

A single-phase five-level inverter was built using MATLAB Simulink, the model built is shown in figure four. Pulse Generators control the switches of this SMLI, on a period of .02seconds as to build a voltage of 50Hz frequency, each DC voltage source is 110V.

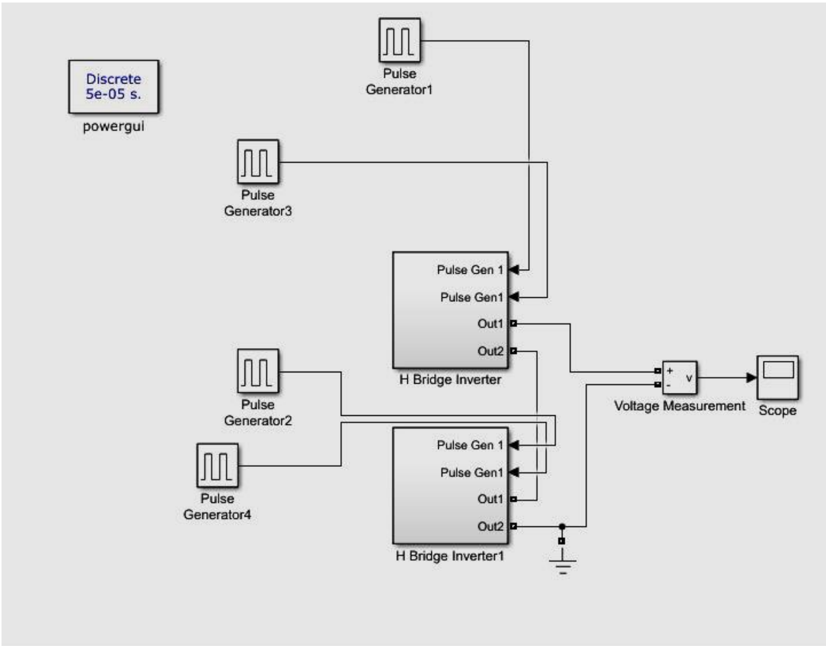

Figure 3.7. Single Phase Five-Level Inverter Model

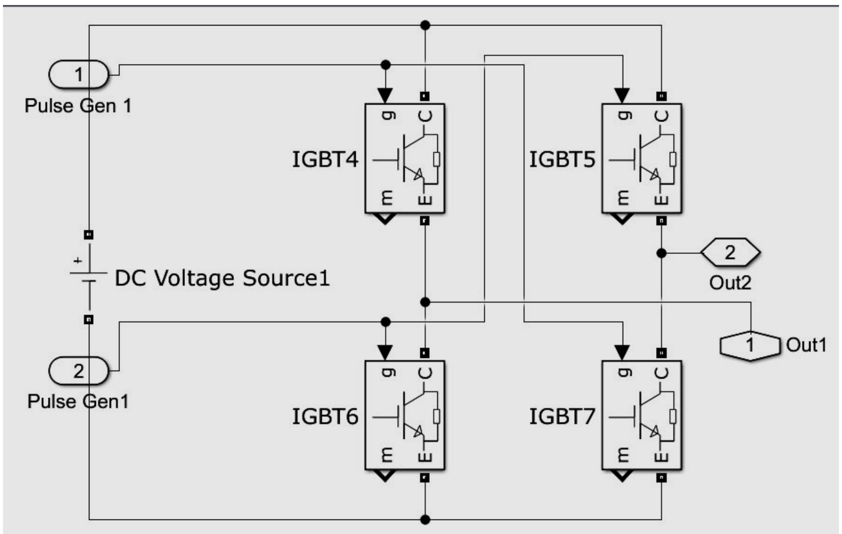

Figure 3.8. Inside model of H-Bridge Inverter

IGBTs modules were used over MOSFET due to its high voltage capability, low ON-resistance, ease of drive, relatively fast switching speeds [15].

The simulation result for the voltage measurement unit is shown in figure (3.7).

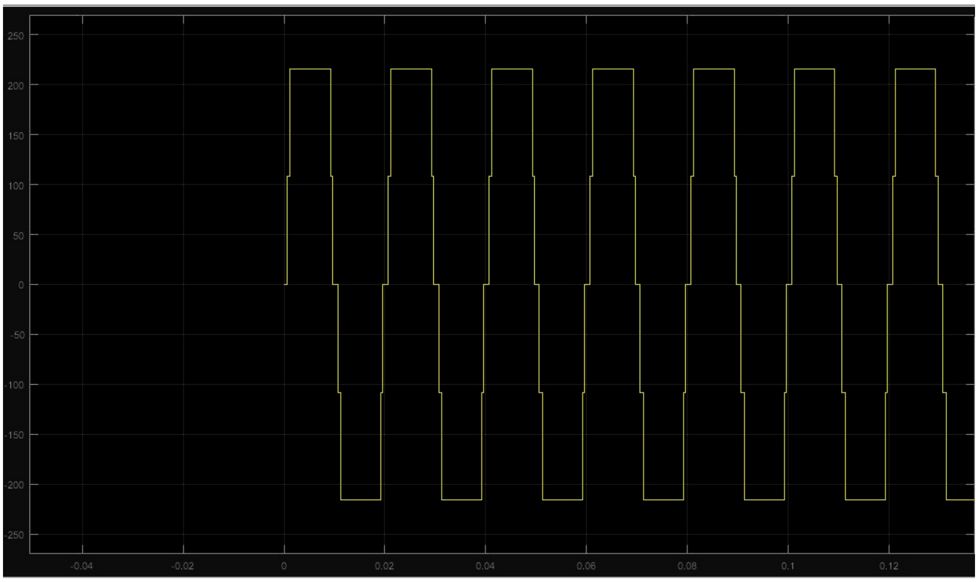

Figure 3.9.Output Voltage of Regular PWM

The firing angle, the angle at which the IGBT was turned on were randomly selected as to achieve the basic voltage waveform of a five-level multilevel inverter.

The FFT analysis of the generated waveform is as shown in figure (3.8).

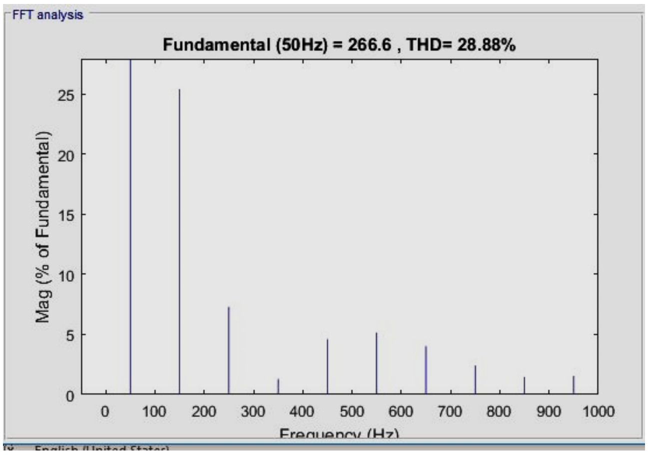

Figure 3.10. FFT Analysis for a regular MLI

In order to reduce harmonics in the generated signal, a second order RC filter was implemented and the output voltage and FFT analysis are shown in figures (3.9) and (3.10) respectively.

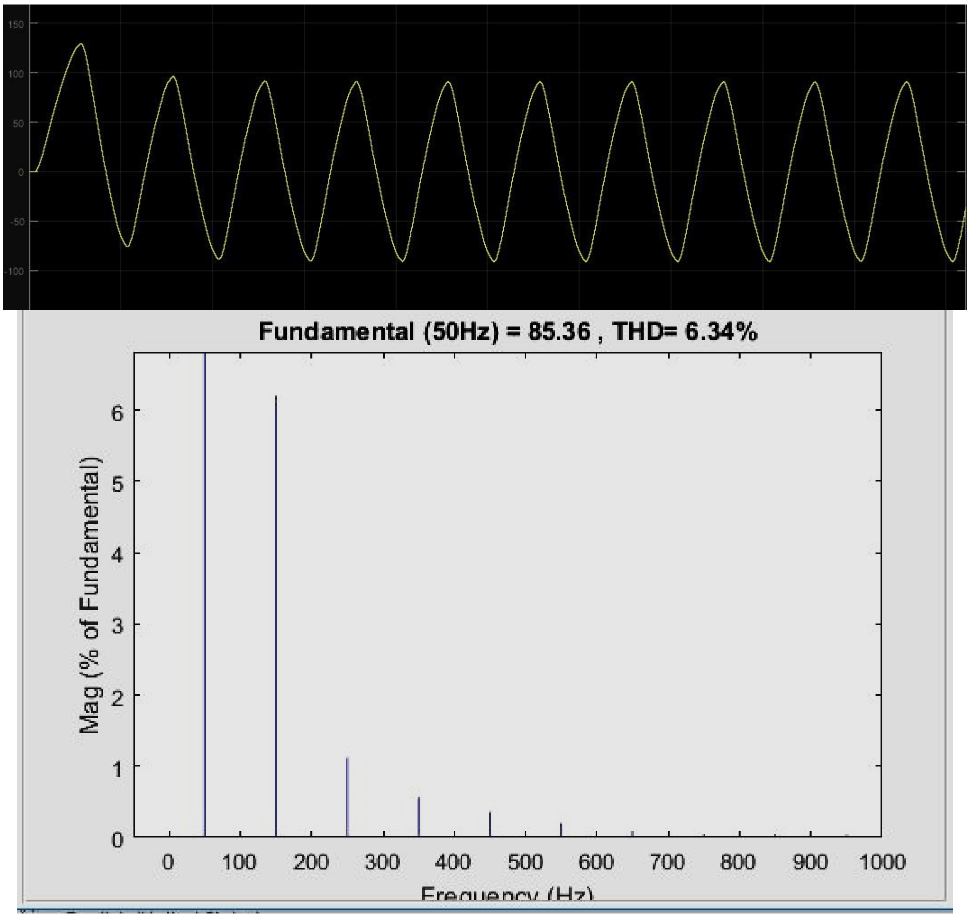

Figure 3.11.Results of a regular MLI with 2nd Order RC filter

- **MCPWM technique:**

The MCPWM technique and output voltage are illustrated in figures (3.10) and (3.11) respectively.

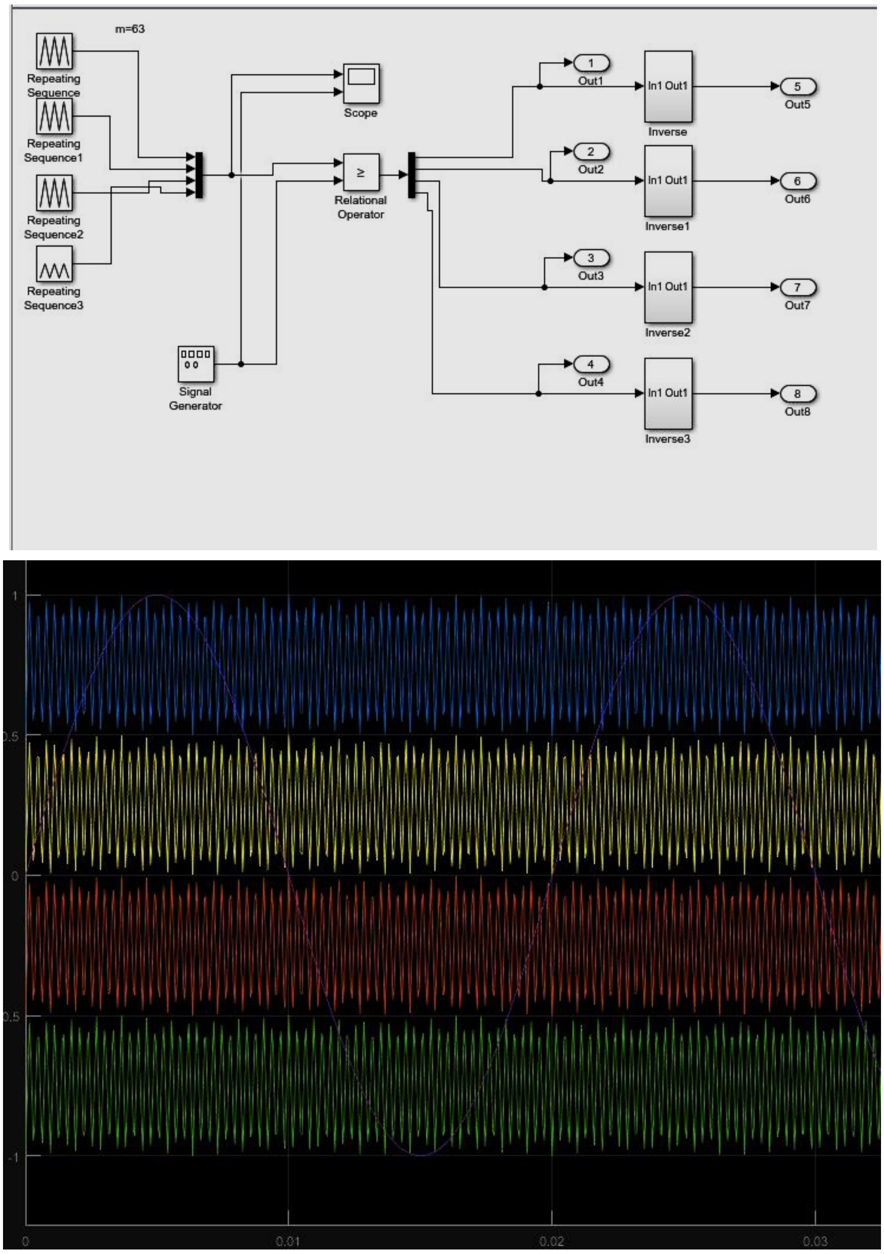

Figure 3.12. Simulink Model and output Waveform of MCPWM

Four triangular signals vertically shifted were used to control a five-level inverter according to the following equation, where S is the number of triangular signals needed.

$$S = N - 1 \text{ [16]---------------------------------(3.10)}$$

At each instant, if the triangular signal is larger than the sinusoidal one, the output of that particular switch is one, otherwise it's zero. To further explain what's happening within a single H-Bridge unit during a MCPWM, referring back to figure (3.1), each IGBT has a diode facing to the opposite direction of the transistor, when the first and fourth transistors are switched on, both the current and voltage are positive, when one of them is switched off, the voltage difference across the load is zero while the current is allowed to flow across the diode in a negative direction. The same concept is applied on the second and third IGBTs.

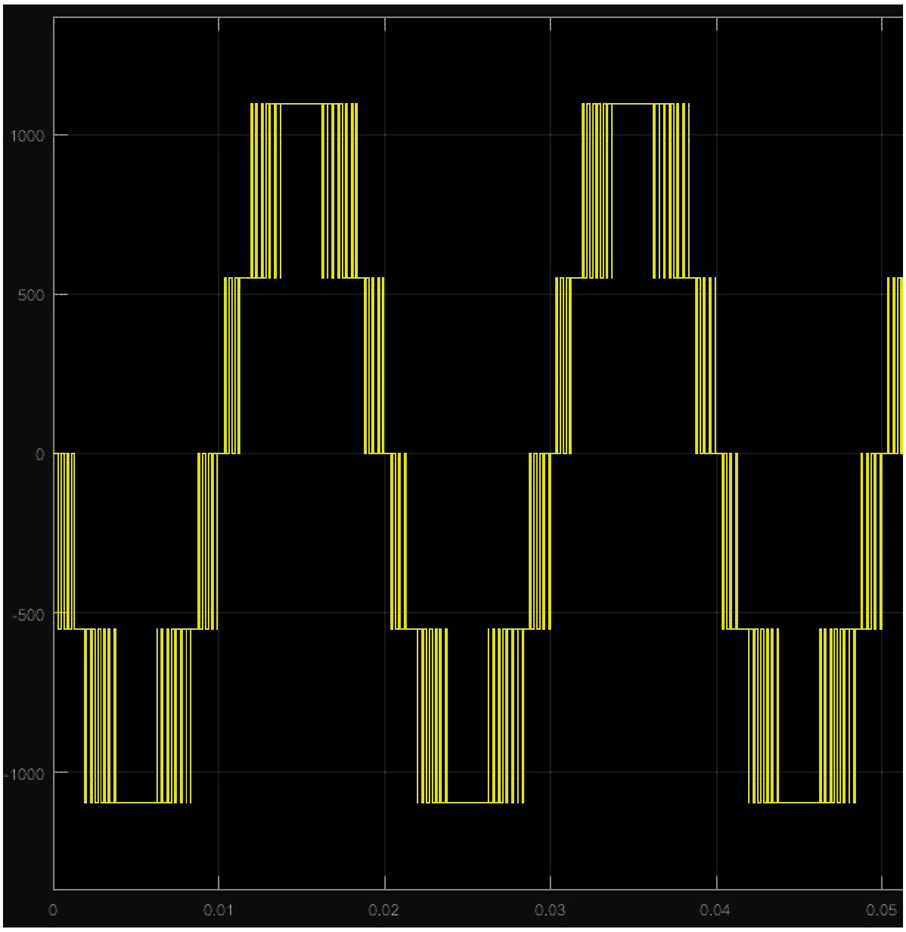

Figure 3.13. Output Voltage Waveform of MCPWM with m=63

The term modulation index indicates the ratio between the amplitude of refence signal and carrier signal, while the term modulation rate indicates the ratio between the frequency of the carrier to the frequency of the reference signal [17].

Modulation index and modulation rate are expressed in the form of equations as follows:

$$r = \frac{2*Ar}{(n-1)Ac} \text{--}(3.11)$$

$$m = \frac{Fc}{Fr} \text{---}(3.12)$$

We can control the amplitude and frequency of the output voltage by changing the amplitude and frequency of the reference signal, while we can improve the performance of the inverter by increasing the modulation rate. The THD values against varying modulation rate is shown in table (3.1).

Table 3.1. m against THD without filter

Modulation Rate (m) equation (3.12)	**THD**
50	27
42	26.81
27	26.9
20	26.80
10	25.86
5	28.66
1	17.33

However, after applying the 2nd order RC filter, the results were as follows:

Table 3.2. m against THD with filter

Modulation Rate (m)	**THD**
50	7.27
42	7.37
27	7.29
20	7.33
10	7.25
5	6.71
1	8.45

It's observed that for the signal quality to improve, a low pass filter should be used along with MCPWM.

Then the modulation rate was stabilized at m=5, and varied the modulation index, the results are shown in table (3.3).

Table 3.3. Modulation Index against THD for m=5

Modulation Index (r)	THD
.1	No signal
.25	No signal
.4	No signal
.55	22.52
.7	20.67
.85	17.83
.95	8.09

- **HES using ANN**

In order to solve the set of equations presented in (2.8), trust region reflective algorithm was used, using MATLAB. The results are illustrated in table (3.4).

Table 3.4. Firing angles with varying modulation index using HES

Modulation Index (r)	α_1	α_2	THD with filter	THD without filter
1	31.5253	31.5484	4.57	31.91
.9	31.6717	31.6717	4.57	32.44
.8	31.8027	31.8131	4.57	32.53
.7	31.9454	31.9454	4.57	32.44
.6	32.0843	32.0843	4.56	32.10
.5	32.2211	32.2283	4.57	33.21
.4	32.3666	32.3666	4.57	32.44
.3	32.5192	32.5010	4.62	33.16
.2	32.6537	32.6568	4.62	33.21
.1	32.8020	32.8020	4.62	32.44

The FFT analysis for HES with modulation index (r = .6) is shown in figure (3.13).

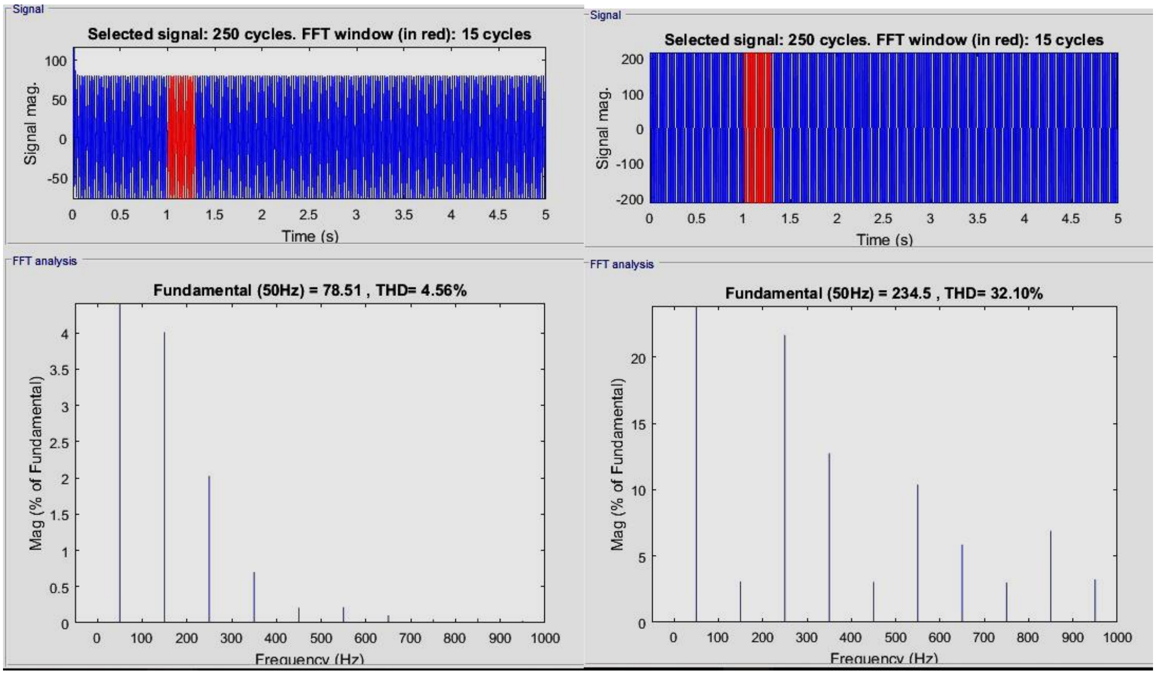

Figure 3.14. FFT analysis with filter (left) and without (right)

Artificial Neural Networks have been used to map between the modulation index and the firing angles, MATLAB neural fitting tool was used. Bayesian algorithm was applied due to its good generalization for small and noisy datasets although, although it takes more time to apply.

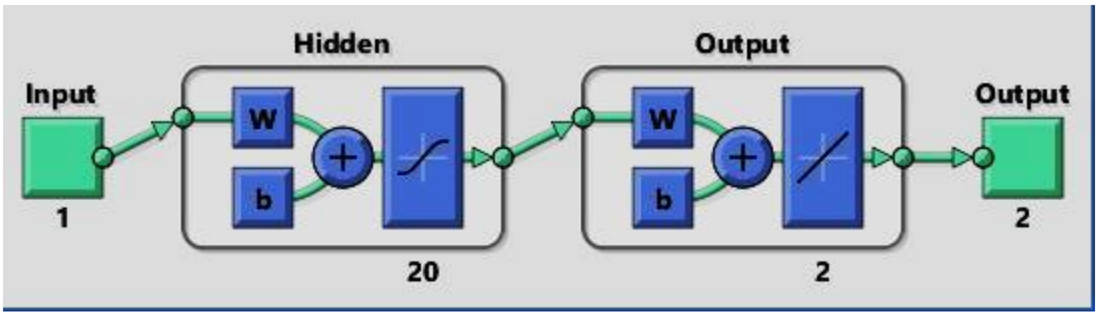

Figure 3.15. ANN diagram used for function approximation

The fit graph and regression plot are shown on figure (3.15) and (3.16) respectively.

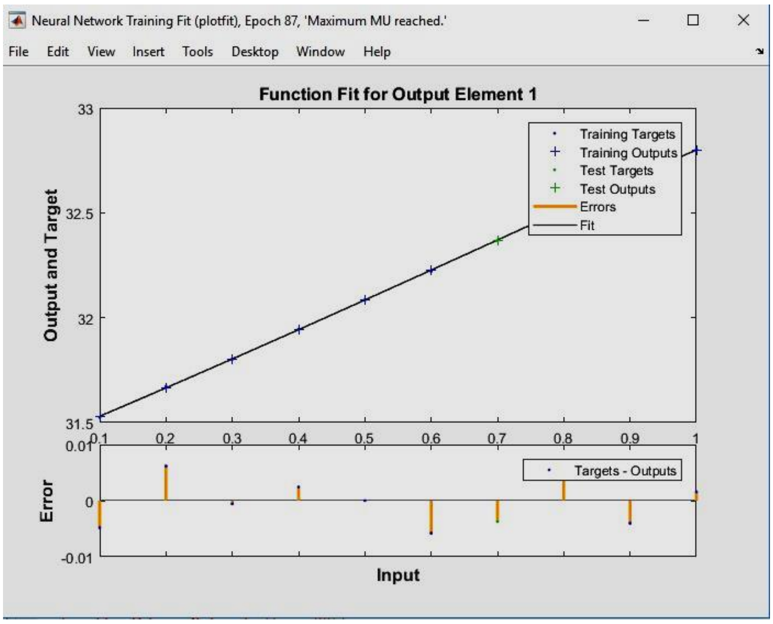

Figure 3.16. fit graph of the trained ANN

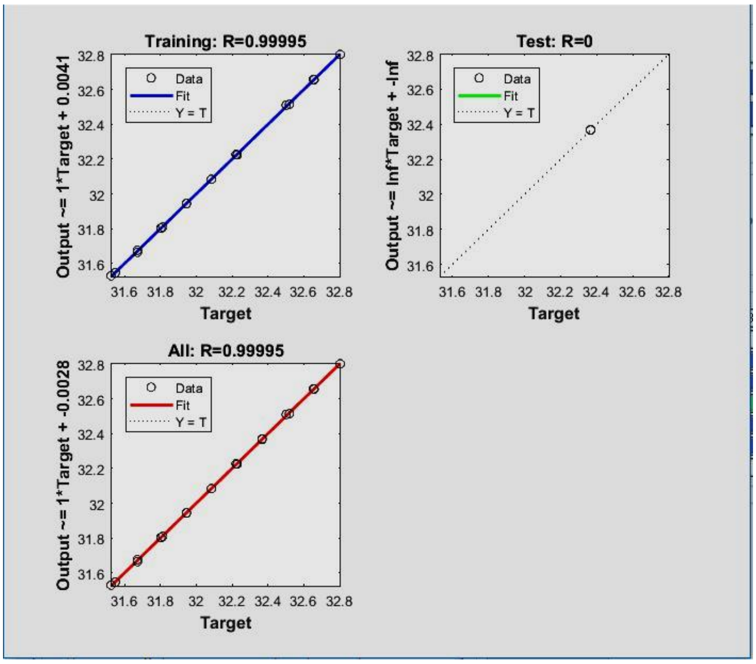

Figure 3.17. Regression plot for the trained ANN.

A test data of new modulation indices has been applied on the ANN, the results are shown in table (3.5).

Table 3.5. HES using ANN results

Modulation Index (r)	α_1	α_2	THD with filter	THD without filter
.7	32.3694	32.3664	4.57	32.44
.15	31.5973	31.6105	4.57	32.11
.26	31.7465	31.7546	4.57	32.44
.38	31.9130	31.9164	4.57	32.44
.44	31.9974	31.9989	4.56	32.44
.57	32.1825	32.1809	4.57	33.44
.63	32.2686	32.2662	4.57	32.44
.76	32.4559	32.4528	4.62	33.16
.89	32.6431	32.6407	4.62	33.16
.94	32.7147	32.7129	4.62	33.16

And the FFT analysis of (r =.89) is shown in figure (3.17).

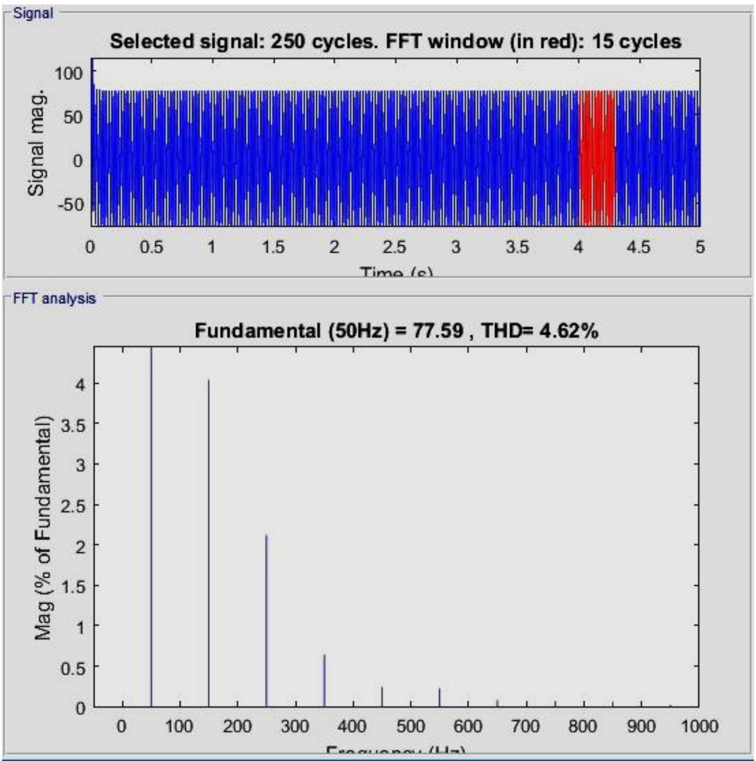

Figure 3.18. FFT analysis of (r=.89)

Chapter 4

OBSERVATIONS

1. In uniform step 5-level inverter, without applying any technique, the majority of the harmonic distortion was due to the third harmonic, then fifth.
2. In MCPWM, the sample time of the power GUI in Simulink matters greatly in simulating high modulation rate.
3. increasing modulation rate doesn't necessarily improve the simulated signal, without using low pass filter the signal was even worse; indicating that what MCPWM actually does is shifting the harmonics away from the fundamental component.
4. In HES, the firing angles resulting from solving the simultaneous equations only partially satisfied the conditions; while it did limit the third harmonic, but it mostly failed to control the amplitude of the signal.
5. Without the filter, the signal of harmonics elimination strategy is feasible, it gives a solid signal for the whole range of modulation index while the signal of MCPWM offers better signal in terms of THD but for limited modulation indices and more signal losses.
6. The 2^{nd} order low pass filter causes enormous loss to the signal.

Chapter 5

CONCLUSION AND RECOMMENDATION

The purpose of using the multilevel inverter is to provide a more efficient conversion of DC to AC. Looking at the results and comparing the values in the tables, the HES is performing better results in terms of overall THD and amplitude control, and the application of ANN enables us to choose between infinite values[1] of modulation index instantly. The results of MCPWM are similar to the uniform step multilevel inverter; this is specially seen in modulation rate of (m = 1) where it gave the minimum THD without using filter, this is a strong indication that the applied MCPWM technique in this study needs modification and optimization to objectively judge and compare it to other methods.

Steps to be taken to further this study and improve this review would include using a better algorithm for solving the system of equations provided by the conditions, including newer type of algorithms such as genetic algorithms. Another step would be to increase the number of levels of the multilevel inverter; since the true advantage of the multilevel inverter manifests with adding more levels, by adding more levels there would be less needed to use the low pass filter and spare the signal losses.

The final step of an improved version of the study would be applying the optimal technique on a real-life application and obtain empirical results.

[1] Infinite values between 0 and 1 is meant in this statement.

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